A Novel Extraction Approach of Extrinsic and Intrinsic Parameters of InGaAs/GaN pHEMTs

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Abstract — **A novel extraction approach of extrinsic and intrinsic parameters of InGaAs/GaN pHEMTs is presented, for the first time, artificial bee colony algorithm is applied to the global-optimization based parameter extraction and a novel intrinsic Y-parameter error function is proposed, which is not sensitive to noise and measurement uncertainty, and also highly consistent to the overall S-parameter error function. The extrinsic elements are optimized at multi-bias points and the intrinsic ones at specific bias points. Only broad ranges of extrinsic parameters are required, and the extraction is unique and accurate. This method has been verified by 2×75 and 4×100 um gate width InGaAs pHEMTs from 1 GHz to 40 GHz. Excellent agreement is achieved between the measured and modeled S-parameters at all the biases and the conservation of the gate charge is well satisfied which further validates this novel extraction method.**

Index Terms —**InGaAs/GaN pHEMTs, artificial bee colony, parameter extraction, intrinsic Y-parameter error function**

I. INTRODUCTION

Good transistor models are essential for the design of nonlinear microwave and RF circuits. Many approaches have been proposed in the last few decades for the extraction of small signal equivalent circuit parameters (ECPs), among which optimization based parameter extraction methods are commonly used due to their flexibility to various equivalent circuit topologies.

Shirakawa [1] proposed a novel approach that intrinsic elements are analytically described by measured S-parameters and extrinsic components, and variances of intrinsic elements are used as one of the reference error [2]. However, there are a few factors which could degenerate the robustness of this method, firstly, variances of the intrinsic parameters are vulnerable to the noise and measurement uncertainty, especially for the non-quasi-static elements like R_{gs}, R_{gd}, and τ, which could improperly dominate the error reference; secondly, it is difficult to find an practical and efficient way to determine the normalization factors between the variances of the intrinsic parameters considering they have distinguished contribution to the overall S-parameters and different sensitivity to the noise.

In this paper, a novel extraction method is proposed that the above deficiencies are overcome. The error function is composed by the overall S-parameter error and novel intrinsic Y-parameter error. The internal elements are analytically obtained, and the discrepancy between the modeled and de-embedded intrinsic Y-parameters is taken as one of the objective error reference instead of the variances of the intrinsic parameters. The new error references are resilient to the noise, since they are dominated by trans-capacitance and trans-conductance, rather than the noisy non-quasi-static elements R_{gs}, R_{gd}, and τ. These two error references are quite consistent with each other, and the normalization procedure is easy and obvious. In addition, multi-bias points are involved in the optimization in order to increase the uniqueness of the extraction. Artificial bee colony (ABC) algorithm is adopted as the optimizer due to its excellent ability to escape the local minimum, and resent major improvements [3] of the ABC has been transplanted in this paper, which leads to much better global searching ability and faster convergence speed.
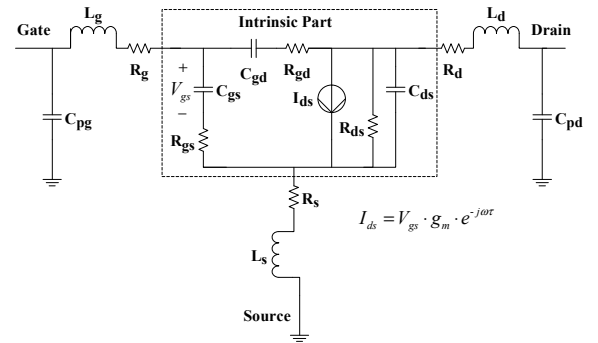

Fig. 1 16-element small signal equivalent circuit of InGaAs/GaN pHEMTs

II. METHOD DESCRIPTION

The adopted 16-element equivalent circuit is given in Fig.1. The intrinsic part is within the dashed lines and the respective Y-parameters Y^{int} are described as:

$$\begin{bmatrix} \dfrac{j\omega C_{gs}}{1+j\omega R_{gs}C_{gs}} + \dfrac{j\omega C_{gd}}{1+j\omega R_{gd}C_{gd}} & -\dfrac{j\omega C_{gd}}{1+j\omega R_{gd}C_{gd}} \\ \dfrac{g_m e^{-j\omega\tau}}{1+j\omega R_{gs}C_{gs}} - \dfrac{j\omega C_{gd}}{1+j\omega R_{gd}C_{gd}} & g_{ds}+j\omega C_{ds} + \dfrac{j\omega C_{gd}}{1+j\omega R_{gd}C_{gd}} \end{bmatrix} \quad (1)$$

A. Novel Objective Function One

If a set of extrinsic parameters are updated by the algorithm, then the intrinsic Y-parameters Y^{int_de} can be obtained by de-embedding technique. Intrinsic elements can be analytically described by the real and imaginary part of Y^{int} [2], so they are estimated by averaging the analytical expressions along frequencies, with the estimated intrinsic elements, internal Y-parameters Y^{int_cal} can be calculated according to equation (1). Discrepancy between the de-embedded Y^{int_de} and calculated Y^{int_cal} is taken as one of the sub-objective function:

$$\varepsilon_{ij}^{sub1}(V_{gs}, V_{ds}, f_k)$$
$$= \frac{|Re(Y_{ij}^{int\_de} - Y_{ij}^{int\_cal})|^p + |Im(Y_{ij}^{int\_de} - Y_{ij}^{int\_cal})|^p}{\max(|Y_{ij}^{int\_de}|^p)} \quad (2)$$

$$\varepsilon_{sub1} = \frac{1}{4 N_f N_{bias}} \sum_{bias} \left(\sum_{i,j=1}^{2} \sum_{k=1}^{N_f} \varepsilon_{ij}^{sub1}(V_{gs}, V_{ds}, f_k) \right)^{1/p} \quad (3)$$

where N_{bias} is the number of the bias points involved, N_f is the number of the frequency points. p is either 1 or 2, usually norm-1 error form is more tolerant of noise than norm-2 error form, so the value of p should be chosen depending on the noise of the measured data.

Noise and measurement uncertainty could easily affect the variances of the intrinsic parameters, and some of the intrinsic elements sometimes do not keep constants against the frequencies, so minimization of the variances do not necessary indicate the agreement between the measured and modeled S-parameters, and these practical deficiencies would seriously degenerate the robustness of the extraction. In this novel internal Y-parameter error function, intrinsic elements are obtained by averaging the analytical expressions along frequencies, so the effect of noise is minimized, even noisy elements like R_{gd}, and τ will not affect the Y-parameter error too much, since they are not the dominating factors of the internal Y-parameters.

Due to the highly similarity between the novel intrinsic Y-parameter error and overall S-parameter (objective function two) error forms, the levels of them are almost the same, so additional normalization factors are not necessary. The accuracy of internal part will also lead to the accuracy of the overall S-parameters, so the two objective functions are highly consistent with each other.

B. Objective Function Two

In order to increase the robustness and accuracy of the extraction, error between the measured and simulated S-parameters is included in the objective function and it is given by:

$$\varepsilon_{ij}^{sub2} = \frac{|Re(S_{ij}^m - S_{ij}^{cal})|^p + |Im(S_{ij}^m - S_{ij}^{cal})|^p}{\max(|S_{ij}^m|^p)} \quad (4)$$

$$\varepsilon_{sub2} = \frac{1}{4 N_f N_{bias}} \sum_{bias} \left(\sum_{i,j=1}^{2} \sum_{k=1}^{N_f} \varepsilon_{ij}^{sub2}(V_{gs}, V_{ds}, f_k) \right)^{1/p} \quad (5)$$

where S_{ij}^m is the measured S-parameter and S_{ij}^{cal} is the calculated S-parameter.

C. Total Objective Function

The total objective function is obtained by simple weighed summation of the two sub-objective functions:

$$\varepsilon_{total} = w_1 \varepsilon_{sub1} + w_2 \varepsilon_{sub2}$$

Where w_i (i =1, 2) is the weighing factor, it is reasonable to let w_i be equal due to the same level of the two sub-objective errors. The total error function not only ensures the accuracy of the overall S-parameters but also the internal Y-parameters, thus making the extracted parameters more accurate and reliable.

III. METHOD VERIFICATION

Two different types of InGaAs pHEMTs (2×75 and 4×100 um) from WIN® pp15-22 0.15um GaAs/InGaAs foundry are employed to verify this novel method. 9 bias points (VGS:{-1.5V,-1V,-0.5V}, VDS :{ 2V, 3V, 4V}) are involved in the optimization. Table I shows the errors between the simulated and measured S-parameters of 99 different bias points (VGS from -2V to 0V with step of 0.25V and VDS from 0V to 5V with step of 0.5V). The overall root-mean-square (RMS) and maximal S-parameter modeling errors are within 2.91% and 4.46% for the two investigated InGaAs pHEMTs, which indicates the high accuracy of the extraction. Fig.2 and Fig.3 also shows excellent agreement between the modeled and measured S-parameters performances.

Except the S-parameter response, measured and extracted small signal capacitances should be verified for charge conservation:

$$\frac{\partial C_{gs}(V_{gs}, V_{gd})}{\partial V_{gd}} = \frac{\partial C_{gd}(V_{gs}, V_{gd})}{\partial V_{gs}} \quad (6)$$

However, the above equation is difficult to validate, since the capacitances are extracted in the domain of V_{gs} and V_{ds}. Alternately, equation (6) can be transformed to [4]

$$\frac{\partial(C_{gs} + C_{gd})}{\partial V_{ds}} = -\frac{\partial C_{gd}}{\partial V_{gs}} \quad (7)$$

It is clearly shown in the Fig.4 that the extracted capacitances are well conserved which indicates that the extracted parameters are physically correct and very suitable for the large signal gate charge construction.

In order to test the uniqueness of this novel extraction method, 15 independent extractions are performed. The results are shown in Table II and the bias point is arbitrarily chosen for illustration. AVG are the average extracted parameters, and σ is the corresponding standard deviation. It is obvious that the extraction is relatively unique noticing that σ is small compared with the average extracted parameters. The start values are randomly generated within the searching space by ABC algorithm, so the uniqueness of the extraction means that the optimization is independent of start values, in another words, the extracted parameters are global optimum.

This novel method can also be applied to other transistors devices with various external topologies and semiconductor manufacturing processes, and the only difference is that distinguishing de-embedding procedures should be performed.

TABLE I
ERRORS BETWEEN THE SIMULATED AND MEASURED S-PARAMETERS OF THE INVESTIGATE 2×75 AND 4×100 UM GATE WIDTH INGAAS PHEMTS (GW=GATE WIDTH)

Err. GW	S_{11} (%)		S_{12} (%)		S_{21} (%)		S_{22} (%)	
	Max	RMS	Max	RMS	Max	RMS	Max	RMS
2×75um	0.63	0.46	4.46	1.67	1.31	1.14	1.14	0.83
4×100um	0.44	0.35	2.16	1.11	2.16	1.43	3.38	2.91

TABLE II
EXTRACTED PARAMETERS OF 2×75 UM GATE WIDTH INGAAS PHEMT, AT VGS=-1V, VDS=5V, 15 INDEPENDENT EXTRACTIONS ARE PERFORMED TO TEST THE UNIQUENESS

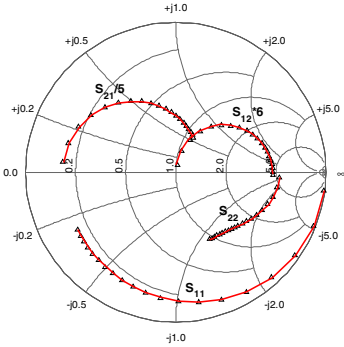| Circuit element	Extrinsic elements		Circuit element	Intrinsic elements	
	AVG	σ		AVG	σ
C_{pg}/fF	2.43	0.20	C_{gs}/fF	157.4	0.25
C_{pd}/fF	8.66	0.17	C_{gd}/fF	15.23	5.7e-3
L_g/pH	31.13	0.076	C_{ds}/fF	20.76	0.16
L_d/pH	20.89	0.30	R_{gs}/ Ω	0.611	0.033
L_s/pH	1.15	0.025	g_{ds}/mS	3.95	1.9e-3
R_g/ Ω	4.15	0.029	g_m/mS	49.00	0.022
R_d/ Ω	6.87	0.091	τ /pS	0.825	0.004
R_s/ Ω	1.43	7e-4	R_{gd}/ Ω	0.71	0.01

Fig.2 Simulated (solid lines) and measured S-parameters (symbols) of 2×75 um gate width InGaAs pHEMT at VGS=-1, VDS=5V from 1-40 GHz.
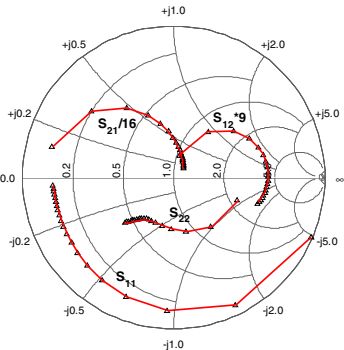

Fig.3 Simulated (solid lines) and measured S-parameters (symbols) of 4×100 um gate width InGaAs pHEMT at VGS=-0.5, VDS=5V from 1-40 GHz.
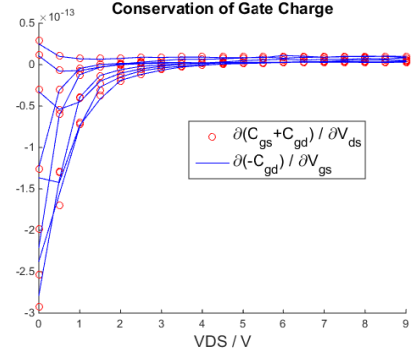

Fig.4 Verification of the gate charge conservation of 4×100 um gate width InGaAs pHEMT

IV. CONCLUSION

A novel extraction approach of extrinsic and intrinsic parameters of InGaAs/GaN pHEMTs is proposed. The extraction is robust, unique and accurate. For the first time, artificial bee colony algorithm is applied to the global-optimization parameter extraction, and a novel intrinsic Y-parameter error function is proposed which is not sensitive to noise and highly consistent to the overall S-parameter error function. This method can also be easily extended to other transistors with various external topologies.

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